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Learning to Modulate Sensorimotor Rhythms with Stereo Auditory Feedback for a Brain-Computer Interface

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***Abstract*— Motor imagery can be used to modulate sensorimotor rhythms (SMR) enabling detection of voltage fluctuations on the surface of the scalp using electroencephalographic (EEG) electrodes. Feedback is essential in learning how to intentionally modulate SMR in non-muscular communication using a brain-computer interface (BCI). A BCI that is not reliant upon the visual modality for feedback is an attractive means of communication for the blind and the vision impaired and to release the visual channel for other purposes during BCI usage. The aim of this study is to demonstrate the feasibility of replacing the traditional visual feedback modality with stereo auditory feedback. Twenty participants split into equal groups took part in ten BCI sessions involving motor imagery. The visual feedback group performed best using two performance measures but did not show improvement over time whilst the auditory group improved as the study progressed. Multiple loudspeaker presentation of audio allows the listener to intuitively assign each of two classes to the corresponding lateral position in a free-field listening environment.**

I. Introduction

It is predicted that by 2050 the number of people in the UK with sight loss will double to almost four million due largely to the increase in the aging population [1]. Although BCI may not be their first choice of assistive technology, there is a need to investigate brain-computer interfaces (BCI) which are not dependent on the visual channel and which may prove beneficial. Feedback is essential for learning in sensorimotor (SMR) based BCI and it is therefore important at this point to make the distinction between audio exogenous/stimulus dependent, and audio endogenous/ mental task BCI. This paper focuses on the latter, as there are limited BCI studies based on auditory feedback alone. The following subsection provides a short review of research using both types of BCI involving the auditory channel.

A. Audio Exogenous BCI

A P300 based auditory speller paradigm was proposed in [2] and was designed for use as a T9 style spelling device. The study used both auditory pitch and lateral position in a 3x3 matrix (9 classes). However, the highest selection accuracy was achieved when examining classes associated with lower pitch or frequency. They also stated that auditory evoked potential (AEP) differences associated with pitch were easier to classify than direction which supports the findings of [3] that showed the effect of amplitude, direction and pitch of stimuli. An interesting approach was proposed by Schreuder et al. [4] where a P300 multi-class BCI made use of loudspeakers spaced equally in front of the listener to present stimuli. Rear speakers were omitted due to a high instance of confusion with frontally placed speakers. This problem was overcome by Rutkowski et al. [5] with the inclusion of "*steady-state tonal frequency stimuli*" and multichannel empirical mode decomposition (EMD) allowing the use of rear speakers and increasing the number of classes.

B. Audio Endogenous BCI

An auditory BCI based on the regulation of slow cortical potentials (SCP) was developed by Pham et al. [6]. They compared the performance of their SCP BCI using visual, auditory and audio/visual feedback groups and although the visual group performed best overall, the auditory group were able to use the system with some degree of success. However, the lower performance was attributed to biophysical shortcomings and the possibly increased mental load due to the feedback being difficult to interpret.

Nijboer et al. [7] used auditory feedback with a sensorimotor rhythm based BCI. The study included 16 able-bodied participants split into 2 equal groups receiving visual or auditory feedback. In this study each class is assigned a different sound effect presented monaurally (mono). However, this presentation method did not seem a logically instinctual technique and could be improved upon with the incorporation of stereophonic (stereo) placement. Nevertheless, it was concluded that their auditory BCI is at least as effective as the visual equivalent when examining a 2 class SMR BCI.

Hinterberger et al. [8][9] used their Thought Translation Device (TTD) to provide sonification of SCP changes whilst a later study [10] included tests using the lateralization of a MIDI double bass sound with varied pitches to indicate changes in the EEG but recommends a comparative study between audio and visual feedback methods.

In this work we propose the use of broadband noise using a modified stereophonic presentation method which would allow the listener to use their innate hearing abilities to intuitively assign each of 2 classes to a corresponding

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speaker location when placed at ±90° azimuth. To date no BCI study has utilised broadband noise, commonly used in auditory localisation experiments [11][12], presented as stereophonic auditory feedback for an audio endogenous SMR based BCI. The results of a comparison between 20 participants split equally into two groups based on the feedback type provided, show that although the visual group performs better initially, the auditory group improves steadily over time and is projected to reach a similar level of performance in just two additional sessions.

II. MATERIALS AND METHODS

A. Participants

The study included 20 healthy participants divided equally into visual and auditory groups. Each group consisted of 5 males and 5 females. All participants were novice BCI users aged between 19 and 37 years old (visual group: 25.3 ±5.8, auditory group: 26.7 ±5.5) and were remunerated at £10/hr. The study was reviewed by the University of Ulster Research Ethics Committee and National Rehabilitation Hospital of Ireland Medical Ethics Committee.

B. Experimental Setup

Subjects were asked to attend 2 sessions per week spaced approximately 2 days apart. Each subject took part in 10 sessions each lasting approximately 1hr. A session consisted of 4 runs of 40 trials with each trial lasting 7s with approximately 2s between each trial. Hence, each subject partook in 1600 trials. Subjects in the visual group were seated in a chair approximately 1m from a computer monitor. Each auditory group member was seated approximately 1m from a wall on which they were asked to remain focused on an 'X' in order to mimic the visual group. Loudspeakers were placed at angles of ±90° azimuth (Fig. 1) and at a distance of approximately 40cm. Session 1 for both groups was used as a training session and hence no feedback was given. During this session EEG was recorded, parameters were tuned and a classifier was trained to provide feedback for the subsequent 2 sessions. Session 4 mirrored session 1 and was used to train a classifier to provide feedback for the subsequent 3 sessions. When session 7 was reached, offline data from the preceding sessions were analysed and the session with the greatest peak classification accuracy, calculated offline using 5 fold cross validation, was chosen to retrain the classifier and was then used for the remaining 3 sessions. During the training session participants were asked to perform motor imagery lasting 4s. Each subject chose a hand/arm motor task they felt most comfortable with.

C. EEG Recording and BCI

EEG was recorded over the sensorimotor cortex using 3 bipolar channels at positions C3, C4 and Cz with the reference taken from the left mastoid. A passive EasyCap system was utilised with 7 Ag/AgCl electrodes. The g.BSamp from g.tec (http://www.gtec.at) was used to amplify the signals before being passed to a National Instruments data acquisition PCI card for digitisation at 125Hz. Subject-specific frequency bands were selected automatically and 'neural time-series prediction pre-processing' was employed using neural networks in conjunction with common spatial patterns (CSPs) with linear discriminant analysis (LDA)[13]. Further information on the BCI translation algorithms are presented in [14][15].

D. Visual Feedback

The visual feedback presented to the visual group was based on the traditional ball and basket paradigm whereby the aim is to direct a ball into one of two baskets. The ball appears and is stationary for 1s before moving toward the bottom of the screen over 3s. Motor imagery (MI) of the left hand/arm causes the ball to move towards the left whilst imagining right hand/arm movement causes the ball to move towards the right of the screen. Lateral movement of the ball around a central zero point is controlled by the signed distance/magnitude of the classifier output. A point was scored for every correctly placed ball and a final score out of a possible maximum of 40 was presented to each subject at the end of each run.

E. Auditory Feedback

Feedback was presented to each participant using a pair of Tannoy Reveal 5A loudspeakers and a low latency MOTU Ultralite Mk3 audio interface. Broadband 1/f or pink noise was used as this contains cues above and below 1.5kHz which are both necessary for accurate localisation of a sound [16]. This was important as the differences in the classification output were to be translated to a location in a wide stereo field. A target spoken command of "left" or "right" was presented originating from the corresponding speaker. Feedback was then given which would move between ±90° azimuth. Left hand/arm MI causes the noise, or 'auditory cursor' to move towards the left, whilst right hand/arm MI causes the noise to move towards the right of the stereo field, again with the classifier distance output indicated by the amount of lateral movement. The aim was to position the auditory cursor at the correct position by the end of each trial which matched the timings of the visual group's task. A point was scored if this was achieved and a final score was presented at the end of each run.

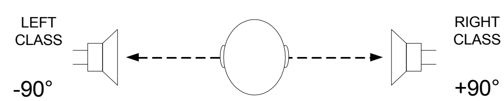

Figure 1. Modified stereophonic speaker positions

F. Analysis

Average performance between groups is reported using two measures: mean classification accuracy (CA) defined as the percentage of trials which coincided correctly with the class label (calculated offline using 5-fold cross validation) and single trial peak classification accuracy (pCA) calculated across-session. Results are given from a 10 × 2 repeated-measures ANOVA performed on pCA results using group as between subject and sessions as within subject factors.

III. Results

According to Müller-Putz et al. [17] when considering a 2 class model, a chance level of 50% should be used only in conjunction with a confidence interval. With 80 trials per class and a confidence interval where $\alpha = 0.01$, chance level is actually 60%. Hence, the outcome of this study shows that performances of the auditory feedback group are well above chance level and shows conclusively that auditory feedback is a feasible and valuable alternative to its visual equivalent.

A. *Group Comparison*

As expected, the visual feedback group scored better on average using both measures of performance. Little difference exists between either group's performances when examining the CA results (Table 1). However, the greatest difference in group performance is evident with regard to the pCA (Fig 2).The repeated-measures ANOVA, performed on the pCA results, did not reveal a significant interaction effect between session and group and no main effect of session or group.

TABLE I. Two performance measures for both groups

	Average Classification Accuracy (CA, %)	Average Peak Classification Accuracy (pCA, %)
Visual	68.40 ±0.82	66.98 ±1.44
Auditory	67.33 ±1.58	63.54. ±2.01

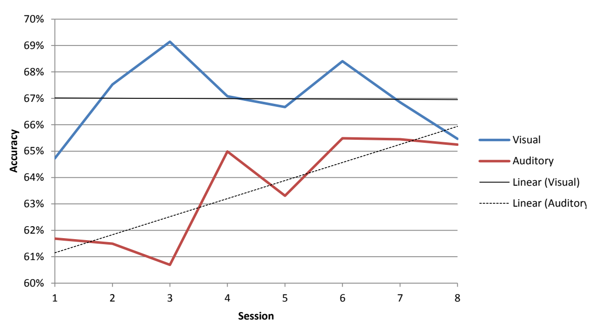

Figure 2. Average peak classification accuracy results for both

B. *Individual Comparison*

Fig. 3 and 4 provide pCA results for the individual members of each group. Linear trends were calculated using linear regression analysis. In the auditory group, only A1 showed a significantly increasing trend ($F = 15.24$, $p = 0.008$); whilst in the visual group only V8 showed a marginally significant positive trend ($F = 5.136$, $p = 0.064$). Whereas only two participants in the auditory group achieved a score over 70% in at least one session, 8 out of 10 in the visual group achieved above 70%. The highest scorer overall was achieved in the auditory group. Furthermore, as can be seen in Fig. 2 the visual group did not show any improvement over the course of the study whereas the auditory group trends indicate that they could reach a similar level of performance in just one or perhaps two more sessions, if the study were to continue for longer.

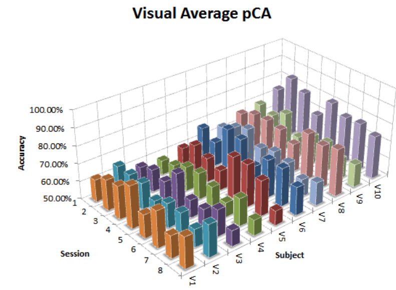

Figure 3. Visual average peak classification accuracy (pAC)

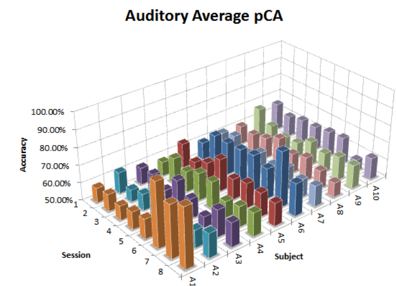

Figure 4. Auditory average peak classification accuracy (pAC)

IV. Discussion

The presentation of audio using this adjusted stereophonic method has yet to be utilised for an SMR based BCI. Other studies examining auditory feedback for an endogenous BCI [6][7][10] suffered from presentation methods which were unnecessarily complex for the listener and may have negatively impacted on the outcome as a consequence. This study, for the first time, makes use of our innate capacity for localisation of a sound source in order to intuitively assign each class accordingly. However, it is difficult to directly compare these two forms of feedback with regards sensory perception and this may have introduced a bias. Overall, the visual group outperformed the auditory group in both measures of performance, yet the auditory group showed the most improvement which is in keeping with findings in [7]. In fact, the visual group showed little or no improvement in performance when measuring pCA. The auditory group conversely, improved over time in both measures. Nevertheless, the results of these experiments were lower in performance than in similar reported studies especially in the visual group. Factors, such as limited channel number, a passive electrode system in a non-shielded room, time between sessions and time between training of classifier data may all have contributed negatively towards the results.

As mentioned earlier, it is not unusual for studies to filter participants in order to obtain an artificially inflated performance average [18][19][20][21][22][23] but this does not accurately represent how a system will operate on the general populace. This study has not excluded anyone on the basis of performance and hence should give a more accurate reflection of results if used by the general public. The system herein makes use of minimal electrodes resulting in a quick set-up and clean-up which need not be supervised by a skilled clinician, making it available to the widest range of users.

V. CONCLUSION

The study aimed to investigate the feasibility of using a BCI successfully with stereo auditory feedback in the absence of its visual equivalent. Results are promising with some individuals scoring well throughout the trials. However, the majority of participants did not reach a sufficient level of performance, generally accepted to be 70% [24], to be usable within the limited experimentation period, although the auditory group did show improvement over time i.e. motor learning. If the study were to continue for longer it is possible that they would reach a sufficient level of control. A parallel study was conducted with a group of physically impaired, mainly spinal cord injury users who received visual feedback across 10 sessions [25]. A subset of this group was subsequently examined with more intensive training sessions addressing some of the issues outlined in the discussion, including the use of active electrodes and same day classifier training [26]. The results show that the improvement can be significant with these enhancements and more intensive training. It is therefore anticipated that audio exogenous BCI using stereophonic feedback can be improved using the enhanced setup and can be a feasible option for BCIs. Plans for additional experimentation are already underway incorporating, firstly, vector-based amplitude panning (VBAP) [27] methods, before integrating headphone presentation and spatialisation techniques into the model. Such features should exploit our innate hearing abilities and progress toward auditory endogenous BCIs which are as conducive to motor learning as the traditional visual feedback paradigms. This should also result in a more natural and intuitive listening experience, improving both feedback and BCI performance.

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